

4. High Global Warming Potential Gases

This chapter presents estimates and projections of high global warming potential (high GWP) emissions in developed countries from 1990 through 2010. High GWP emissions result from the use of substitutes for ozone-depleting substances (ODS) and five additional industrial sectors:

- Several hydrofluorocarbons (HFCs) and, to a lesser extent, perfluorocarbons (PFCs) and hydrofluoroethers (HFEs) are replacing ODS in a wide variety of applications, including as refrigerants, aerosol propellants, solvents, foam blowing agents, medical sterilization carrier gases, and fire extinguishing agents.
- PFCs, SF₆, and HFC-23 are used in semiconductor production.
- HFC-23 is released as a byproduct of HCFC-22 production.
- SF₆ is used as a dielectric gas and insulator in sealed electric power equipment.
- SF₆ is released during its use as a cover gas to protect molten magnesium from burning on contact with air.
- PFCs-CF₄ and C₂F₆-are produced and released during primary aluminum smelting.

4.1 Overview

Exhibit 4-1 summarizes total high GWP emissions by source for 1990 through 2010. Exhibit 4-2 summarizes total high GWP emissions by region. Exhibit 4-3 lists the high GWP gases included in this analysis, along with their associated uses or emission sources, atmospheric lifetime, and global warming potentials. More detailed high GWP emissions and projections are presented in Appendix D.

Exhibit 4-2: Total High GWP Gas Emissions from Developed Countries (MMTCO₂)

Region	1990	1995	2000	2005	2010
EU-15	57	46	80	120	160
Other Western Europe	6	4	5	10	18
Russia	20	15	18	33	53
Eastern Europe	4	2	2	8	15
AUS/NZ	8	5	6	11	12
Japan	15	34	31	58	88
Canada	14	11	13	21	27
U.S.	98	100	140	220	310
Total	223	223	298	489	685

Exhibit 4-1: High GWP Gas Emissions by Source (MMTCO₂)

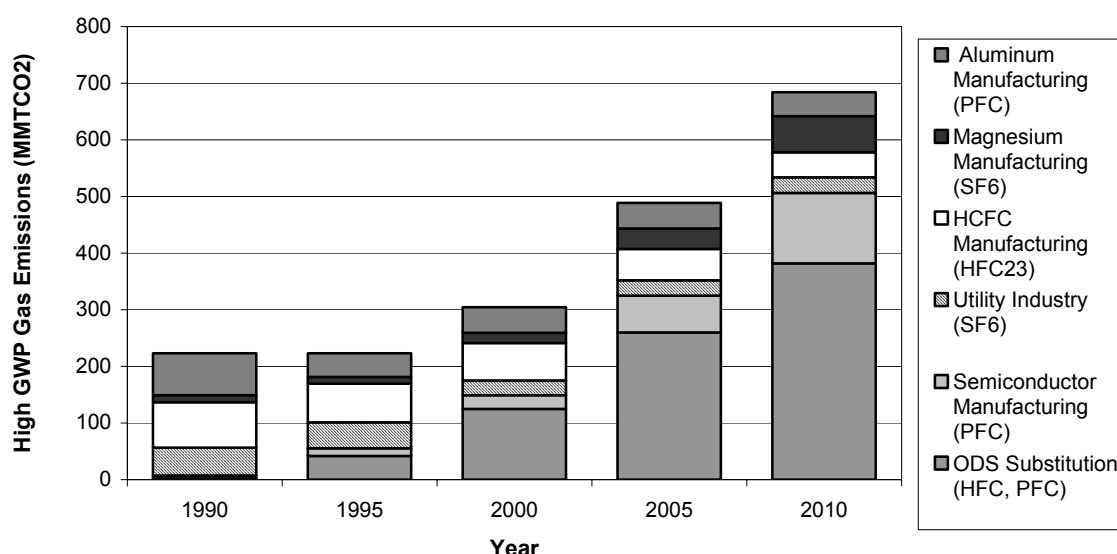


Exhibit 4-3: High GWP Chemicals

Chemical	Life-time (yrs)	GWP (100-yr)	Use
Hydrofluorocarbons (HFCs)			
HFC-23	264	11,700	Byproduct of HCFC-22 production, used in very-low temperature refrigeration, blend component in fire suppression, and plasma etching and cleaning in semiconductor production.
HFC-32	5.6	650	Blend component of numerous refrigerants.
HFC-41	3.7	150	Not in commercial use today.
HFC-43-10mee	17.1	1,300	Cleaning solvent.
HFC-125	32.6	2,800	Blend component of numerous refrigerants and a fire suppressant.
HFC-134	10.6	1,000	Not in commercial use today.
HFC-134a	14.6	1,300	Most widely used HFC refrigerant, blend component of other refrigerants, propellant in metered-dose inhalers and aerosols, and foam blowing agent.
HFC-152a	1.5	140	Blend component of several refrigerant blends.
HFC-143	3.8	300	Not in commercial use today.
HFC-143a	48.3	3,800	Refrigerant blend.
HFC-227ea	36.5	2,900	Fire suppressant and propellant for metered-dose inhalers.
HFC-236fa	209	6,300	Refrigerant and fire suppressant.
HFC-236ea	8.1 ^a	1,000 ^a	Not in commercial use today.
HFC-245fa	7.7 ^{b,c}	816 ^{b,c}	Foam blowing agent and refrigerant; near commercialization.
HFC-245ca	6.6	560	Not in commercial use today, possible refrigerant in the future.
HFC-365mfc	10.2 ^a	910 ^a	Under study for use as foam blowing agent.
Perfluorocarbons (PFCs)			
CF ₄	50,000	6,500	Byproduct of aluminum production. Plasma etching and cleaning in semiconductor production and low temperature refrigerant.
C ₂ F ₆	10,000	9,200	Byproduct of aluminum production. Plasma etching and cleaning in semiconductor production.
C ₃ F ₈	2,600	7,000	Low-temperature refrigerant, and fire suppressant. Used in plasma cleaning in semiconductor production.
C ₄ F ₁₀	2,600	7,000	Fire suppressant.
C-C ₄ F ₈	3,200	8,700	Not in much use, if at all, today. Emerging for plasma etching in semiconductor production.
C ₅ F ₁₂	4,100	7,500	Not in much use, if at all, today.
C ₆ F ₁₄	3,200	7,400	Precision cleaning solvent - low volume use.
Nitrogen Trifluoride (NF₃)			
NF ₃	740 ^d	10,800 ^d	Plasma cleaning in semiconductor production.
Sulfur Hexafluoride (SF₆)			
SF ₆	3,200	23,900	Cover gas in magnesium production and casting, dielectric gas and insulator in electric power equipment, fire suppression discharge agent in military systems, atmospheric and subterranean tracer gas, sound insulation, process flow-rate measurement, medical applications, and formerly an aerosol propellant. Used for plasma etching in semiconductor production.
Hydrofluoroethers (HFEs)			
C ₄ F ₉ OCH ₃	5.0 ^a	390 ^a	Cleaning solvent and heat transfer fluid.
C ₄ F ₉ OC ₂ H ₅	0.77 ^a	55 ^a	Near commercialization for use as a cleaning solvent.
<p>GWPs and atmospheric lives are reprinted from the Intergovernmental Panel on Climate Change, Second Assessment Report, 1995, except as noted below:</p> <p>^aWMO, 1999, Scientific Assessment of Ozone Depletion: 1998, World Meteorological Organization, Global Ozone Research and Monitoring Project – Report No. 44, p.10.27.</p> <p>^bJunyi Chen, Valerie Young, and Hiromi Niki, Kinematic and Mechanistic Studies for Reaction of CF₃CH₂CHF₂ (HFC-245fa) Initiated by H-Atom Abstraction Using Atomic Chlorine, J. Phys. Chem. A 1997, 101, 2648-2653.</p> <p>^cPersonal communication between Don Wuebbles, University of Illinois at Urbana-Campaign and Reynaldo Forte, US Environmental Protection Agency, August 27, 1998.</p> <p>^dIPCC, 2001.</p>			

As the exhibits show, emissions of the high GWP gases have increased during the 1990s and are expected to increase through 2010 in every country, primarily due to increasing emissions of the ODS substitutes as countries' phase out ODS production under the Montreal Protocol.

The major source of potential emissions increase among the other industrial gas uses is the semiconductor industry, which is expected to continue dramatic economic growth throughout the forecast period. High GWP emissions will increase more modestly from the utility and magnesium industries. Emissions from HCFC-22 production are expected to decline after non-feedstock HCFC production is phased out. Emissions from aluminum smelting are projected to decrease over time, although aluminum production is increasing, because of on-going efforts to significantly modify operating parameters and reduce the emissions from this source.

4.2 Substitutes for Ozone Depleting Substances

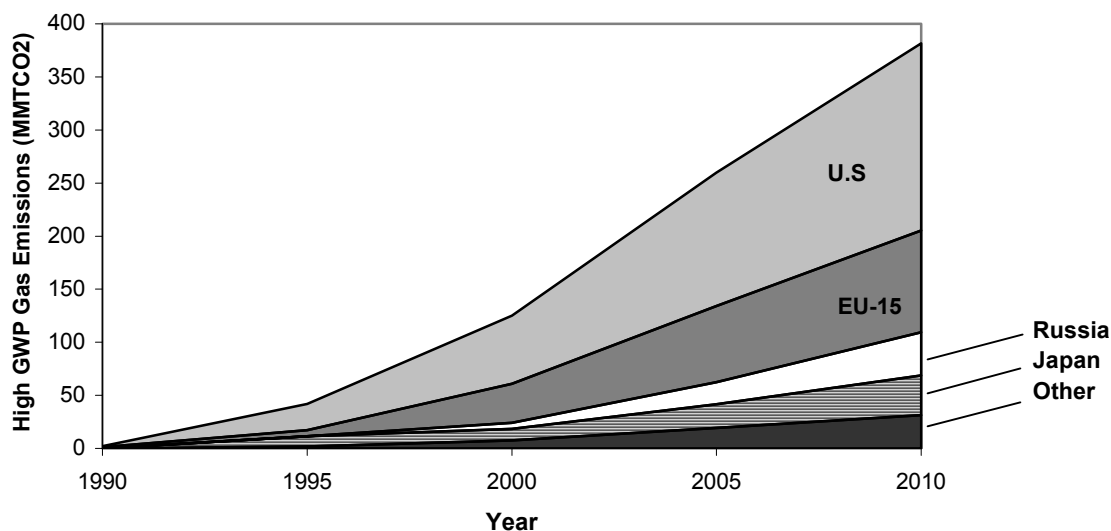
Hydrofluorocarbons (HFCs) and, to a lesser extent, perfluorocarbons (PFCs) and hydrofluoroethers (HFEs) are used as alternatives to several classes of

ozone-depleting substances (ODSs) that are being phased out under the terms of the Montreal Protocol. ODSs, which include chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), have been used for decades in a variety of industrial sectors including refrigeration and air conditioning, aerosols, solvent cleaning, fire extinguishing, foam production, and medical sterilization. Although the HFCs, and PFCs that replace ODSs are not harmful to the stratospheric ozone layer, they are powerful greenhouse gases.

Total Emissions of ODS Substitutes	
Year	MMTCO ₂
1990	2
1995	42
2000	125
2005	260
2010	382

As shown in Exhibit 4-4, the use and subsequent emissions of HFCs and PFCs as ODS substitutes has increased dramatically, from small amounts in 1990, to 127 MMTCO₂ in 2000. This trend is expected to continue for many years, and will accelerate in the early part of this century as HCFCs, which are interim substitutes in many applications, are themselves phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol.

Exhibit 4-4: HFC and PFC Emissions from ODS Substitute Uses 1990 through 2010 (MMTCO₂)



In addition, in some ODS replacement applications, such as solvent cleaning or aerosol applications, the substitutes are emitted immediately, but in others, such as refrigeration and air conditioning applications, the substitutes are replacing ODSs in equipment that slowly releases the gas. Therefore, the rate of increase in ODS substitute emissions is driven by the pace of the phase out in each country and by the emissions profile for the source in which the gas is used.

Significant uncertainty exists in these estimates. In particular, European projections have significantly lower estimates for Europe than those presented here (Ecofys, 2001). Additionally, extrapolating from ODS use in 1990 may be problematic for estimating future HFC use as substitution rates are uncertain.

4.3 Semiconductor Manufacturing

The semiconductor industry currently emits fluorocarbons (CF_4 , C_2F_6 , C_3F_8 , $\text{C-C}_4\text{F}_8$, HFC-23), and sulfur hexafluoride (SF_6) during manufacturing processes. These gases, collectively called perfluorinated carbon compounds (PFCs), are used in two important steps of silicon-based semiconductor manufacturing: (1) plasma etching of thin films; and

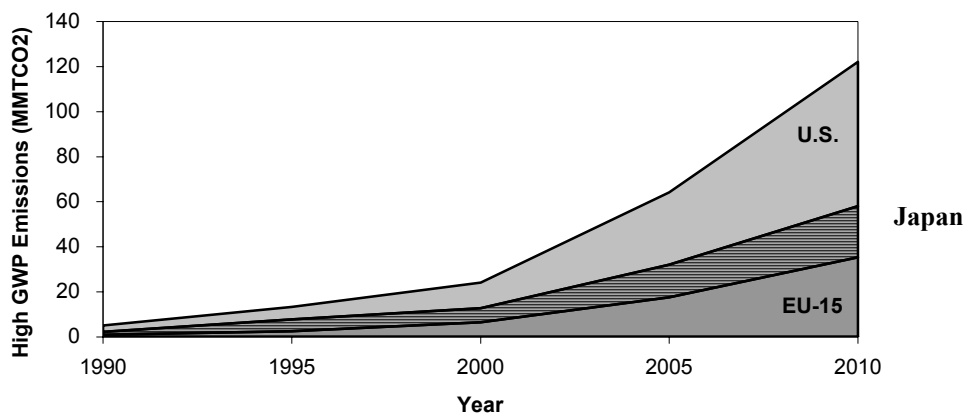
(2) cleaning of chemical-vapor-deposition (CVD) chambers. Some amount of the chemical used in these processes is emitted to the atmosphere. In addition, a fraction of the heavier PFCs used in these two production processes is converted into CF_4 and emitted. The amount of the PFCs used in and emitted during any process varies according to the manufacturer and to the device being manufactured.

Exhibit 4-5 presents estimates of the total emissions from semiconductor manufacturing for the years 1990 through 2010 for developed countries.

Total PFC and SF_6 Emissions from Semiconductor Manufacturing	
Year	MMTCO ₂
1990	5
1995	13
2000	24
2005	65
2010	124

Among developed countries, the majority of PFC emissions originate from the three major semiconductor producing regions: the US, EU-15, and Japan. These three regions are projected to remain the major producers of semiconductors through 2010.

Exhibit 4-5: PFC and SF_6 Emissions from Semiconductor Manufacturing 1990 through 2010 (MMTCO₂)



Market demand for semiconductors is projected to continue its current rapid growth. Correspondingly, a rapid growth in PFC emissions from the semiconductor industry in these three regions is projected. It is important to note that these projections are not inclusive of voluntary climate commitments. The semiconductor industry has taken an aggressive target to reduce PFC emissions. In April 1999, the World Semiconductor Council (WSC) agreed to reduce PFC emissions by at least 10 percent below 1995 levels by 2010. WSC members produce over 90 percent of the world's semiconductors.

4.4 HCFC-22 Production

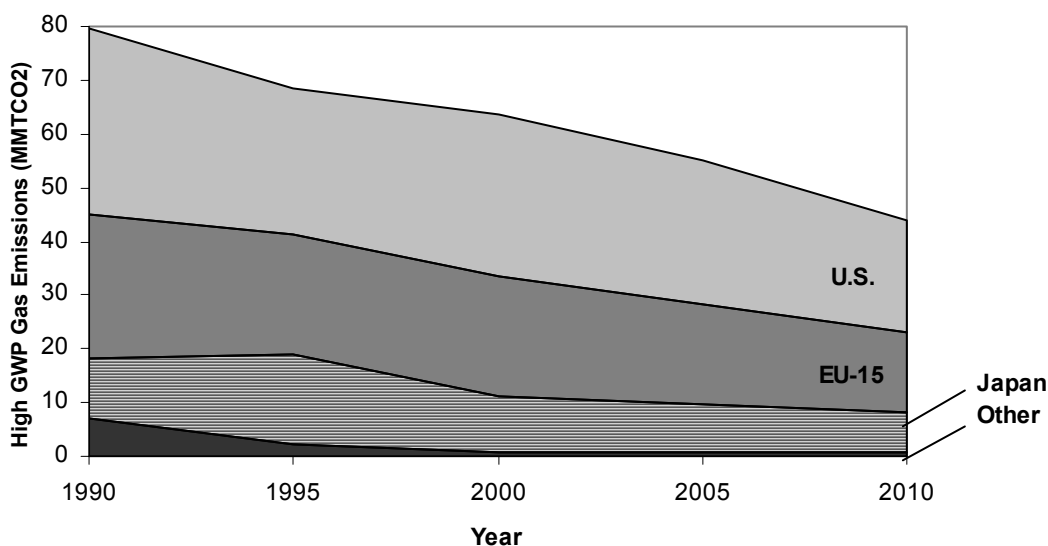
Trifluoromethane (HFC-23) is generated and emitted as a by-product during the production of chlorodifluoromethane (HCFC-22). Nearly all producers in developed countries have implemented process optimization or thermal destruction to reduce HFC-23 emissions. In some cases, however, it is collected and used as a substitute for ozone depleting substances, mainly in very-low temperature refrigeration and air conditioning systems.

HFC-23 emission factors range from 1 to 5 percent per unit of HCFC-22 produced. HFC-23 exhibits the highest global warming potential of the HFCs, 11,700 over a 100-year time horizon, and it has an atmospheric life of 264 years.

Total HFC-23 Emissions from HCFC-22 Production	
Year	MMTCO ₂
1990	80
1995	69
2000	66
2005	63
2010	56

As shown in Exhibit 4-6, HFC-23 emissions from HCFC-22 production decreased overall from 1990 to 2000 with a significant decrease from 1990 to 1995 due to process optimization. Emissions are expected to continue decreasing through 2010. A major reason for the decrease is that HCFC-22 production, for most end-uses, is scheduled to be phased-out by 2030 under the Copenhagen Amendments to the Montreal Protocol. Emissions are not anticipated to decrease to zero, however, because HCFC-22 production for use as a feedstock to other chemicals is permitted to continue indefinitely and feedstock production is anticipated to continue growing steadily, mainly for manufacturing Teflon® and other chemical products.

Exhibit 4-6: HFC-23 Emissions as a Byproduct of HCFC-22 Productions 1990 through 2010 (MMTCO₂)



4.5 Electric Utilities

An estimated 80 percent of the worldwide sales of sulfur hexafluoride (SF₆) are made to electric utilities and manufacturers of equipment used to enable the transmission and distribution of electricity (Rand, 2000). Sulfur hexafluoride has been employed as an insulating gas by the electric power industry since the 1950's because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated high voltage circuit breakers, substations, transformers, and transmission lines. Sulfur hexafluoride has replaced flammable insulating oils in many applications and allows for more compact electrical equipment in dense urban areas.

Fugitive SF₆ can escape from gas-insulated substations (GIS) and gas-insulated circuit breakers through seals, especially from older equipment. It can also be released when equipment is opened for servicing, which typically occurs every few years or when equipment is disposed. In the past, some utilities vented SF₆ to the atmosphere during servicing. Increased awareness and the relatively high cost of the gas have reduced this practice.

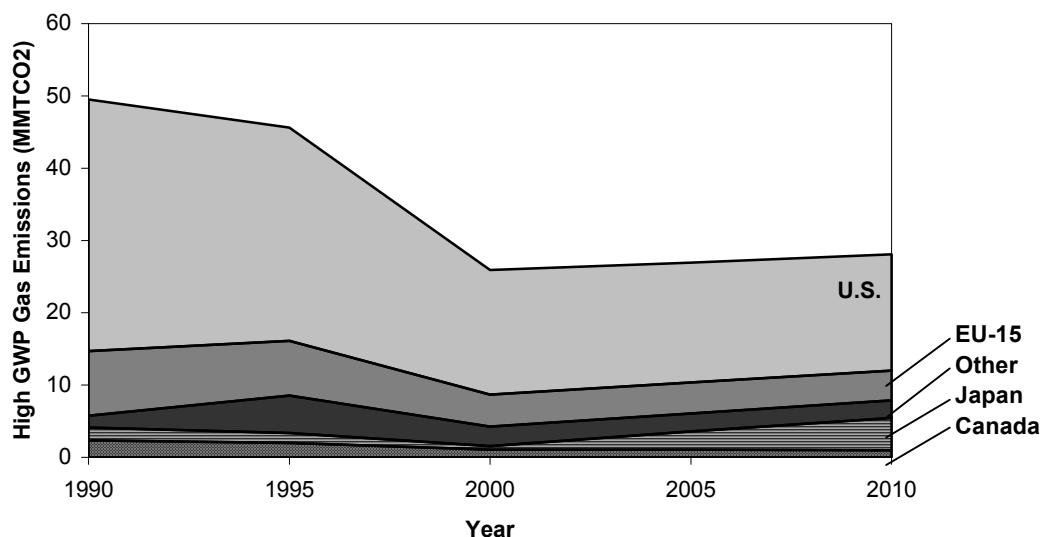
Total SF ₆ Emissions from Electric Utilities	
Year	MMTCO ₂
1990	50
1995	46
2000	26
2005	27
2010	28

As shown in Exhibit 4-7, emissions from electric utilities have steadily decreased since 1990 and are expected to continue decreasing, despite the growth in the electric utility sector. The price increase of SF₆ in the mid-90s encouraged electric power systems to improve equipment maintenance and servicing in order to conserve the gas. The use of leak detection and recycling methods has also increased as utilities strive to lower costs and mitigate environmental effects.

4.6 Magnesium Production

The magnesium metal production and casting industry uses sulfur hexafluoride (SF₆) as a covergas to prevent the violent oxidation of molten magnesium in the presence of air. Small concentrations of SF₆ in

Exhibit 4-7: SF₆ Emissions from Electric Utilities 1990 through 2010 (MMTCO₂)



combination with carbon dioxide and air are blown over the molten magnesium metal to induce the formation of a protective crust. The industry adopted the use of SF₆ to replace sulfur dioxide (SO₂). The SF₆ technique is used by producers of primary magnesium metal and most magnesium parts die casters. The recycling industry employs a variety of melt protection techniques including salt fluxes and SF₆. Exhibit 4-8 presents total SF₆ emissions from magnesium production through the year 2010 for developed countries.

Total SF₆ Emissions from Magnesium Production	
Year	MMTCO₂
1990	13
1995	12
2000	16
2005	32
2010	55

Worldwide, the magnesium production industry is projecting very strong growth between 1990 and 2010. The rate of growth increases after 2000. All regions are projected to experience increased magnesium production, leading to a strong increase in SF₆ emissions in every region. For the U.S., there is a leveling of emissions from magnesium production between 1995 and 2000 due to the closing

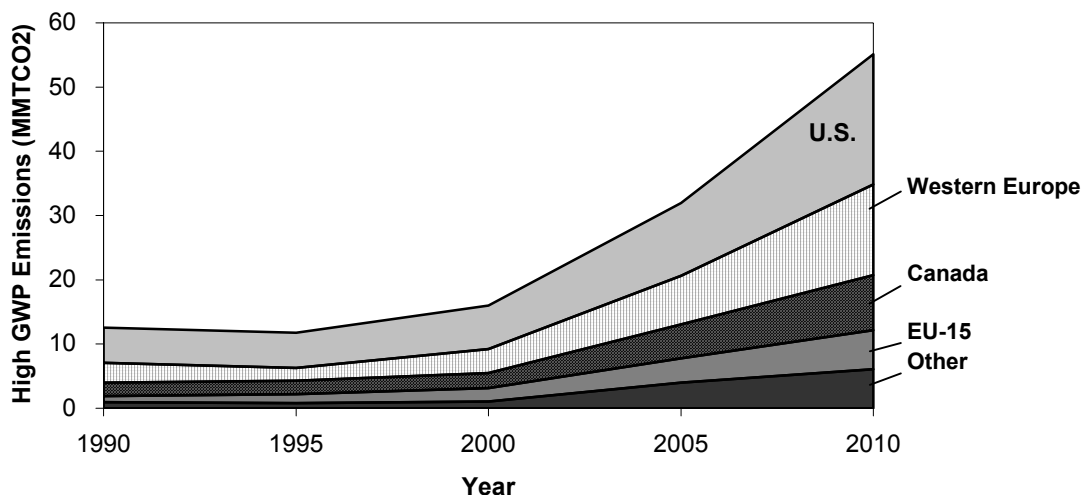
of the largest of the three facilities in the U.S. The two remaining U.S. facilities are expected to regain most of the lost production capacity and resume a trend of net national production growth by 2010, with a corresponding growth in SF₆ by 2010.

4.7 Aluminum Production

The primary aluminum production industry is currently the largest source of PFC emissions. During the aluminum smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, termed “anode effects” (AEs). These anode effects cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF₄ and C₂F₆. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these anode effects: the more frequent and long-lasting the anode effects, the greater the emissions. Exhibit 4-9 presents the total aluminum PFC emissions from industrial sources through the year 2010 for developed countries.

Future PFC emissions will be affected by changes in primary aluminum production and changes in the

Exhibit 4-8: SF₆ Emissions from Magnesium Production 1990 through 2010 (MMTCO₂)



emission rate per ton of aluminum produced. Continued increases in global aluminum production are anticipated through 2010.

Total PFC Emissions from Aluminum Production	
Year	MMTCO₂
1990	74
1995	42
2000	41
2005	42
2010	40

The production growth results from additions to current aluminum capacity, mostly in the developing world, and improvements in cell technology that increase production efficiency at existing smelters worldwide. Emission rates, on the other hand, are expected to decrease as upgrades in process controls and alumina feeding systems will yield shorter, less frequent anode effects. The developed countries as a whole will see a substantial decrease in emissions because of the combined effect of production moving to developing countries and reduced emission rates. In the U.S. and EU-15, aluminum smelters have realized the environmental and economic benefits of reducing the frequency and duration of anode

effects, which cause PFC emissions. This action resulted in a lower emissions rate that will continue into the future.

Exhibit 4-9: PFC Emissions from Primary Aluminum Production 1990 through 2010 (MMTCO₂)

